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A Report of Field Studies

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[illegible] area at the Morton Arboretum, Lisle, Illinois. The picture [illegible]

Fertilization of Established Trees:

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Prior to this study the two senior authors, as plant pathologists, had recommended fertilization as a preventive or corrective control measure for several tree diseases. It was recognized, however, that the procedures for fertilizing established trees had not been thoroughly subjected to scientific evaluation; more experimental data were needed.

While cooperating with the junior author at the Morton Arboretum, Lisle, Illinois, on plant disease studies in 1962 the senior authors learned of an experimental area in the Arboretum which contained uniform, established trees in 100-tree blocks with tree spacing intervals optimum for fertilizer trials. In this area a cooperative study was initiated with the Morton Arboretum.

Following the early successful attempts at measuring growth response to fertilizer applications in 1963 and 1964 at the Morton Arboretum, the senior authors expanded the study with trials at four additional sites in Illinois through 1968.

ACKNOWLEDGMENTS

First our appreciation is expressed to Dr. J. C. Carter, Head of the Section of Botany and Plant Pathology at the Illinois Natural History Survey, for his advice and guidance throughout this study. We also extend our gratitude, for their cooperation during the fertilizer tests in different areas of Illinois, to the following persons who permitted the use of private and public lands: Mrs. C. Philip Miller, owner of Sinnissippi Forest, Oregon, Illinois; Mr. Clarence E. Godschalk, former Director, and Dr. Marion T. Hall, Director of the Morton Arboretum, Lisle, Illinois; Mr. James L. McMillen, Superintendent, Division of Parks and Memorials, Illinois Department of Conservation, Springfield, Illinois; and Mr. T. A. Mehrhoff, Jr., Project Manager, Crab Orchard National Wildlife Refuge, U.S. Fish and Wildlife Service, Carterville, Illinois.

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done by Wilmer Zehr, Technical Photographer; the illustrations were drawn by Richard Sheets, Technical Illustrator; the manuscript was edited by Owen F. Glissendorf, Technical Editor; and Mrs. Betty A. Nelson, Technical Assistant, assisted in the preparation of the manuscript.

REVIEW OF LITERATURE

Application of mineral nutrients to soil to stimulate tree growth has been a subject of discussion by arborists for 40 years or more. Most of the procedures used in tree fertilization have been based on field experiences; few have been based on scientific experimentation.

Forest trees or fruit trees are often used as ornamentals or shade trees. Therefore, experimental results on tree fertilization obtained by foresters and pomologists benefit aborists. A book edited by Childers (1954) reviews the knowledge of mineral nutrients of fruit trees. Since pomologists are mainly interested in fruit production, their experiences are probably not as relevant as those of foresters. Recent symposia at two universities dealt with the mineral nutrition of forest trees—Duke University School of Forestry (1959) and University of Florida (1968). Stoeckeler & Arneman (1960) reviewed the information on fertilizer use in forests. Several hundred papers on forest fertilization research are included in the bibliographies of White & Leaf (1956) and Mustanoja & Leaf (1965). Most forestry fertilizer trials have been conducted in forest nurseries or with evergreen species, not with established deciduous trees.

The number of fertilizer field trials pertinent to the arborist is small. In 1927 and 1928 Jacobs (1929) compared fall application with spring application of fertilizers on American elm and Norway maple street trees. Each species was approximately 5 cm in trunk diameter at a point 1.0–1.2 m above the ground. Jacobs concluded that there was "little difference between fall and spring treatments but a decided benefit from either treatment compared with trees which received no treatment."

Beilmann (1936) also recognized the need for data on the effects of fertilization on shade trees. Although many of his tests did not include control plots, he performed tests on several tree species between 1928 and 1933. He devised a formula for rate of fertilization based on tree height, branch spread, and trunk circumference.

Wyman (1936) reported the results of a well-designed 4-year test on nursery-sized pin oaks. He compared results from two combinations of nutrients on two soil types. His fertilizer treatments began the first growing season following planting. During the first three growing seasons, while the trees were becoming established, tree growth was limited. Wyman reported that the fertilization produced a response in twig growth during the second growing season and a response in trunk diameter growth during the third growing season.

Chadwick (1934, 1937, 1940, 1941) measured the annual response of American elms to four nutrient combinations and three seasons of application from 1932 through 1940. The elms were planted in 1931. The nutrients were nitrogen (N), nitrogen and phosphorus (NP), and nitrogen, phosphorus, and potassium (NPK) combinations. The fertilizer was broadcast on the soil surface. Chadwick (1941) states, "The inconsistency of the data recorded indicate that fertilizer experiments on woody ornamentals out of doors must be of a long-time nature . . . ." His study indicated that fall was as favorable as, or more favorable than, other seasons for application of fertilizers and that NPK or NP combinations of nutrients were more beneficial than N alone.

In a test with established Norway maples approximately 4 cm in trunk diameter at 1.4 m height, Chadwick, Tilford, & Irish (1950) applied NPK mixed with water, air (with an air gun), or peat, on the soil surface and into the soil. They also applied N, P, and K singly and in all possible combinations. Fertilizer treatments were applied in April, 1941 and May, 1947. Growth measurements were made each fall from 1941 through 1948. The results indicated that surface applications of fertilizer resulted in a greater diameter increase than other methods of application and that nitrogen may be considered the limiting element for good growth, but that when nitrogen is coupled with phosphorus a greater stimulation may result.

Other results of tree fertilization field studies in the late 1930's or early 1940's include the report by Chandler (1939) who concluded that heavy applications of nitrogen fertilizers increased twig growth of beech and sugar maple by more than 100 percent. Deuber (1939) found that it was possible to kill young trees by using extremely heavy rates of fertilizer. Pridham (1938), in continued observation of the pin oak plots fertilized by Wyman, stated that after seven growing seasons the untreated trees were as large as the trees fertilized at planting. He stated that variance in growth due to fertilization at time of planting is much less than the variance in growth due to season, soil, time of planting, and method of planting. Pridham was unable to demonstrate a stimulation of trunk diameter growth of large American elms (1940) or red oaks (1941) by fertilization.

Recent reports of tree fertilization field trials include tests on dogwood by Curlin (1962), sweetgum and oak by Broadfoot (1966), tulip tree by Finn & White (1966), and sugar maple and tulip tree by van de Werken & Beavers (1965).

Many nutrients essential to plant growth can enter leaves directly. Pirone (1951) reported results from 3 years of testing foliar applications of nutrients on five species of street trees. He noted that the general appearance of trees receiving six foliar sprays was better than that of untreated trees. His chemical analyses of leaves from a small number of London plane trees and pin oaks showed more nitrogen and phosphorus in leaves from the treated trees than in leaves from untreated trees.

Preliminary data from the tree fertilization field trials at the Morton Arboretum test site reported in detail here were published previously by the authors (1965).

CHARACTERISTICS OF STUDY AREAS

Sites of Fertilizer Plots

The fertilizer trials on deciduous trees (and two species of evergreens) were conducted at five sites in Illinois. The locations of the fertilizer plots are shown on the map of Illinois (Fig. 1).

The site of the original test plot was the Morton Arboretum, Lisle, DuPage County. The Morton Arboretum is a privately endowed educational foundation, founded in 1922 by Joy Morton. The Arboretum is approximately 25 miles west of Chicago.

The second test site was the Illinois Natural History Survey arboretum near Urbana, Champaign County, 1 mile south of the University of Illinois campus. The land is owned by the University of Illinois. It was assigned to the Natural History Survey in 1960.

The third test site was Sinnissippi Forest, a private plantation and naturally forested area along the east bank of the Rock River, 3 miles southeast of Oregon, Ogle County. Although privately owned by Mrs. C. Philip Miller, Sinnissippi Forest is extensively used for scientific purposes and is managed by a University of Illinois resident forester.

The fourth test site was the Lincoln Trail State Park, approximately 3 miles south of Marshall, Clark County. The park is managed by the Illinois Department of Conservation and has a resident

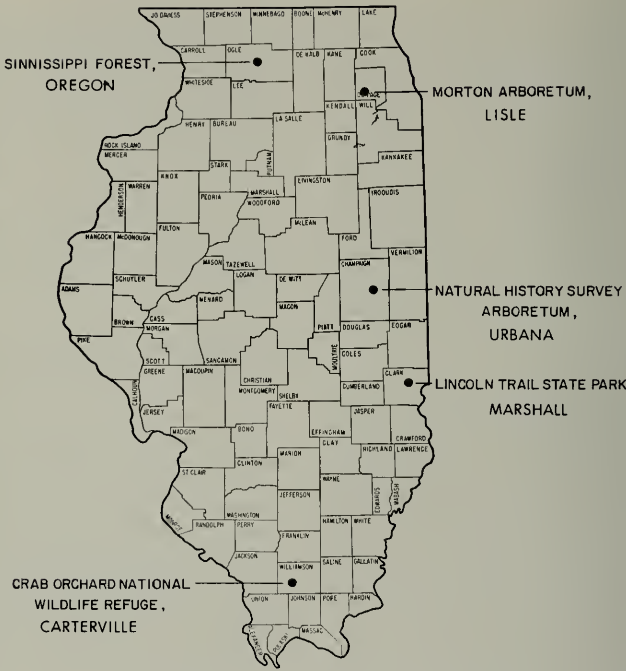

Fig. 1. — The five tree fertilization test sites in Illinois.

ranger. In addition to the natural wooded area surrounding a man-made lake, the park contains numerous deciduous and evergreen tree plantations.

The fifth fertilizer test site was the Crab Orchard National Wildlife Refuge, southeast of Marion, Williamson County. The Refuge is managed by the U.S. Department of the Interior, Fish and Wildlife Service. One of the numerous resident employees is a forester.

Soil Characteristics

In the fertilizer plots in this study at five sites, 10 soil types are represented. The following descriptive information concerning the soil types was primarily obtained from University of Illinois Agricultural Experiment Station Bulletin 725 by Fehrenbacher, Walker, & Wascher (1967).

Loess is the most extensive parent material of Illinois soils. It is a silty material deposited by wind during glacial times. In Illinois, because of the prevailing westerly winds, loess is thickest just east of the sources at the Mississippi and Illinois River Valleys. It thins in a regular manner with distance away from the sources. Glacial drift is also a major source material for Illinois soils. This material was deposited after having been moved by glaciers. The drift deposits are subdivided into glacial outwash, which consists of stratified gravel, sand, silt, or clay deposits, and glacial till, which is unstratified.

Surface soil color is a reasonably good guide to the organic matter content of Illinois soils—the darker the soil the greater the organic matter content. In general, dark-colored soils developed under grass or prairie vegetation and light-colored soils developed under trees or forest vegetation.

The degree of soil development refers to the extent of weathering and change the parent materials have undergone in the formation of the soil. In strongly developed soils the soil profile contains horizons or layers with well differentiated properties of color, texture, and structure.

At the Morton Arboretum the trees in the fertilizer tests were on Andres, Beecher, Markham, and Morley silt loams.

Andres silt loam is a dark-colored grassland soil with moderate development. It formed in silty clay loam glacial till with a mantle of less than 0.5 m of loess or glacial drift. The till is calcareous at 0.5–1.0 m depth. It has a slope of 1–3 percent. The surface soil is a black to very dark brown silt loam 25–40 cm thick with fine crumb to granular structure. The subsurface soil is a very dark brown loam 8–15 cm thick with weak structure. The subsoil is a gray and brown clay loam 30–50 cm thick with imperfect water permeability.

Markham, Morley, and Beecher soils developed from the same parent material as Andres. These, however, are lighter colored, moderately developed soils formed under forest or mixed forest and prairie vegetation.

Markham has a slope of 3–8 percent. The surface soil is a very dark grayish brown silt loam with granular structure 15–20 cm thick. The somewhat lighter colored subsurface soil has weaker structure and is 5–12 cm thick. The subsoil is brown silty clay loam 0.5–1.0 m thick with moderately slow to slow permeability.

Morley has a slope of 4–12 percent. It is quite similar to Markham except that it has a slightly lighter colored and thinner surface soil layer, only 5–12 cm thick, and a thicker subsurface soil layer 8–20 cm thick.

Beecher has a slope of 1–4 percent. It is somewhat poorly drained, since surface runoff is slow to medium and subsoil permeability moderately slow to slow. Otherwise, it is similar to Markham. The surface soil layer is 15–25 cm thick and the subsurface soil layer 8–20 cm thick. There are distinct mottles throughout the subsoil.

At Sinnissippi Forest the fertilizer plots are on Plainfield sand. The Plainfield soils are on nearly level to sloping glacial outwash plains and stream terraces and on sloping to steep morainic areas (2–15 percent slope). They have formed in sandy drift with high quartz and low weatherable mineral content. The soils are excessively drained with surface runoff slow to medium and permeability very rapid. The surface horizon is a dark grayish brown sand 15–25 cm thick and medium acid. The subsoil layer is yellowish brown sand 30–45 cm thick and strongly acid.

The soil in the Natural History Survey aboretum is Flanagan silt loam. It is a dark, moderately developed, grassland soil with a slope of 1–3 percent. It is an imperfectly drained soil that formed in 1.0–1.5 m of loess overlying calcareous loam glacial till. The surface soil is a black to very dark gray silt loam 15–25 cm thick with moderately good structure and medium acidity. The subsurface soil is a dark brown, heavy silt loam 18–30 cm thick. The subsoil is a mottled, brownish, silty clay loam that has moderate permeability and is 75–100 cm thick.

The soil types at Lincoln Trail State Park and Crab Orchard Wildlife Refuge are of similar origin. The four types involved are Stoy, Weir, Bluford, and Wynoose silt loams. All are light-colored, strongly developed soils of southern Illinois that formed under forest vegetation.

Stoy and Weir formed in loess 1–3 m thick on Illinois drift (largely till) or from more than 2 m of loess on bedrock residuum. Stoy has a slope of 1–4 percent. The surface soil is a dark brown friable silt loam with weak crumb structure, strongly acid, and 12–18 cm thick. The subsurface soil is pale brown and 25–35 cm thick. The subsoil is a gray and brown silty clay loam with slow water permeability. Weir has a slope of 0–2 percent. Soil profile depths and colors are similar to those of Stoy. The subsoil contains slightly more clay. Drainage is poor to very poor with runoff slow to medium and permeability slow.

Wynoose and Bluford are very strongly developed soils that formed in 0.5–1.2 m of loess on Illinois glacial drift (largely till) and their subsoil horizons usually extend into the till. Wynoose is quite similar in topography, profile, texture, structure, and reaction to Weir. Bluford is similar to Stoy in these same characteristics.

Data on the available plant nutrient supply as determined by soil tests were obtained from untreated soils from the five test sites. Soil samples collected at the Morton Arboretum from the upper 30 cm of soil and at the Survey arboretum from the upper 15 cm of soil were tested in 1965. Soil samples from the Crab Orchard Refuge, Lincoln Trail State Park, and Sinnissippi Forest plots were collected from the upper 15 cm of soil and tested in 1968. Averages of the soil test data from the tree fertilizer plots are given in Table 1. Additional properties of these soil types are also included in the table.

Precipitation Data

Along with soil fertility, a factor that greatly influences the growth of trees is soil moisture. The precipitation data from the U.S. Weather Bureau collecting stations nearest the fertilizer test sites give an indication of the abundance or sparsity of soil moisture throughout the growing season.

The precipitation data collecting stations were relatively close to the five fertilizer test sites. The collecting stations were located 4 miles northwest of the Morton Arboretum until June 1966 when the station was moved to the Arboretum, 1 mile north of the Survey arboretum, 15 miles east of Sinnissippi Forest, 4 miles northeast of Lincoln Trail State Park, and 4 miles northeast

Table 1. — Soil test data for the soils at the fertilizer test sites.

	Typical Properties[a]			*Soil Tests From Tree Plots*			
Soil Type	Organic Carbon, Percent	Cation Exchange Capacity, m/100 g	Base Saturation, Percent	Number of Samples	pH	P kg/ha	K kg/ha
Andres	. . .	. . .	. .	15	6.4	18	213
Beecher	3.5	17.2	87	. .	. . .	. .	. . .
Markham	. . .	. . .	. .	. .	. . .	. .	. . .
Morley	1.1	12.2	. .	. .	. . .	. .	. . .
Flanagan	3.0	20.3	73	10	7.0	21	336
Plainfield	0.9	4.0	20	4	5.6	27	129
Wynoose	1.3	9.5	28	5	5.4	9	155
Stoy	1.2	10.4	39	1	5.1	16	222
Weir	0.7	13.6	69	1	5.8	9	113
Bluford	1.8	15.4	17	. .	. . .	. .	. . .

[a] From Fehrenbacher & Odell (1959), Wascher, Veale, & Odell (1962), and unpublished data of Dr. J. B. Fehrenbacher University of Illinois Department of Agronomy.

Table 2. — Precipitation data per quarter year from U.S. Weather Bureau collecting stations nearest the five fertilizer test sites during those years tests were in progress.

Location and Growing Season	Rainfall, cm				
	Oct. Nov. Dec.	Jan. Feb. Mar.	Apr. May June	July Aug. Sept.	Total
Morton Arboretum					
1962–63	5.8	10.3	26.5	26.2	68.8
1963–64	9.2	10.7	24.9	31.6	76.4
1964–65	10.3	22.6	22.8	43.4	99.1
1965–66	16.7	13.9	35.0	13.4	79.0
1966–67	21.5	12.9	34.7	20.2	89.3
1967–68	23.3	9.9	28.4	36.0	97.6
NHS Arboretum					
1963–64	11.7	19.3	38.9	18.2	88.1
1964–65	13.6	20.6	31.4	45.5	111.1
1965–66	15.4	11.1	27.1	26.9	80.5
Sinnissippi Forest					
1964–65	9.5	14.8	29.0	46.9	100.2
1965–66	19.4	8.4	32.9	13.0	73.7
1966–67	19.8	12.0	31.8	18.3	81.9
1967–68	21.5	5.6	25.7	33.7	86.5
Lincoln Trail					
1965–66	15.0	11.6	28.7	17.5	72.8
1966–67	28.0	19.2	28.3	26.4	101.9
1967–68	40.0	15.5	35.2	26.7	117.4
Crab Orchard					
1965–66	10.6	21.4	44.8	23.0	99.8
1966–67	27.7	17.9	29.1	19.4	94.1
1967–68	36.0	21.5	27.5	17.8	102.8

of the Crab Orchard Wildlife Refuge. The precipitation data at the five test sites for those years in which fertilizer trials were in progress are given in Table 2.

Tree Species and Spacing

Twenty-two species of trees were used in the fertilizer trials in 29 test plots at the five test sites. Twenty were deciduous species and two were evergreen species.

DECIDUOUS TREES

Acer platanoides L. ....Norway maple
A. rubrum L. ....Red maple
A. saccharum Marsh. ....Sugar maple
Carya illinoensis (Wang.) K. Koch ....Pecan
Crataegus oxyacantha Pauli' Rehd. ....Paul's scarlet hawthorn
Diospyros virginiana L. ....Persimmon
Fraxinus americana L. ....White ash
F. pennsylvanica var. *subintegerrima* (Vahl.) Fern. ....Green ash
Gleditsia triacanthos L. f. *inermis* (L.) Zabel ....Honey locust
Juglans nigra L. ....Black walnut
Liquidambar styraciflua L. ....Sweet gum
Liriodendron tulipifera L. ....Tulip tree
Platanus occidentalis L. ....Sycamore
Quercus alba L. ....White oak
Q. bicolor Willd. ....Swamp white oak
Q. rubra L. ....Red oak

Q. palustris Muench. ....Pin oak

Tilia americana L. ....Basswood

T. cordata Mill. ....Littleleaf linden

Ulmus parvifolia Jacq. ....Chinese elm

EVERGREEN TREES

Pinus resinosa Ait. ....Red pine

P. taeda L. ....Loblolly pine

Trees in 26 of the 29 test plots were in plantations. Within each plot these

Table 3. — Age, spacing distance, percentage survival, and size of trees in plantations at the five fertilizer test sites, and the type of soil in which the trees were growing.

Site, Test, and Tree Species	*Year of Planting*	*Planting Distance Between Trees, m*	*Planting Survival, Percent*	*Initial[a] Trunk Diameter, cm*	*Soil Type*
Morton Aboretum					
Method					
White ash	1956	4.6 x 6.1	100	7.9	Andres
Honey locust	1957	4.6 x 6.1	66	4.3	"
Pin oak	1956	4.6 x 6.1	100	4.1	"
Time					
Pin oak	1956	4.6 x 6.1	98	5.3	"
Rate					
White ash	1956	4.6 x 6.1	100	8.1	"
Species response					
Basswood	1924	2.4 x 2.4	50	24.6	Beecher
Norway maple	1924	2.4 x 2.4	33	19.5	Markham
Red maple	1924	2.4 x 2.4	67	18.3	"
Sugar maple	1924	2.4 x 2.4	52	17.1	"
Red oak	1926	2.4 x 2.4	60	15.5	Morley
Swamp white oak	1926	2.4 x 2.4	58	12.2	"
White oak	....[b]	±9.0 x 9.0	..	45.4	Beecher
NHS Arboretum					
Species response					
Green ash	1960	1.5 x 1.8	100	2.6	Flanagan
Chinese elm	1961	1.5 x 2.1	100	2.2	"
Hawthorn	1960	1.5 x 1.8	100	2.3	"
Littleleaf linden	1962	1.5 x 2.1	100	1.3	"
Norway maple	1962	1.5 x 1.8	100	1.7	"
Sinnissippi Forest					
Method					
Green ash	1941	2.4 x 2.4	80	11.2	Plainfield
Red pine	1942	2.1 x 2.1	100	14.1	"
Sycamore	1941	2.4 x 2.4	67	12.2	"
Black walnut	1942	2.4 x 2.4	85	10.6	"
Lincoln Trail					
Method					
Loblolly pine	1951	1.8 x 1.8	86	13.7	Wynoose
Persimmon	....[b]	±3.0 x 3.0	..	9.3	"
Sweet gum	1951	1.8 x 1.8	75	10.9	"
Sycamore	1951	1.8 x 1.8	68	8.2	"
Tulip tree	1951	1.8 x 1.8	50	10.7	"
Crab Orchard					
Species response					
Pecan	1938	15.3 x 15.3	90	40.6	Weir
Sweet gum	1938	1.2 x 1.2	41	9.7	Stoy
Black walnut	....[b]	±4.0 x 4.0	..	17.3	Bluford

[a] Average of trunk diameters immediately prior to initial fertilization.
[b] In a natural stand.

trees were of the same age, had a uniform spacing between trees, and within a narrow range had a uniform size. The spacing distances in the different plots varied from 1.2 to 15.3 m (4–50 ft.) between trees. Uniform spacing was a primary factor in selecting test plots and sites; however, in most plots not all the trees originally planted were surviving when the testing began. In three of the test plots, the trees were in naturally regenerated stands. Table 3 lists the tree species used at each of the five sites and gives the planting date, the original spacing between trees, the percentage of tree survival, tree size when testing began, and the soil type.

MATERIALS AND METHODS

In this study the initial tests were aimed specifically at determining what nutrients would stimulate a growth response in established trees when applied in various ways. Sixteen fertilizer treatments were used and each treatment consisted of a different combination of fertilizer and method of application. Later tests were designed to give more limited data that would confirm or fail to confirm the results obtained from the initial tests by utilizing additional species of trees growing in different soil types and locations.

The nutrient elements used in varying amounts and combinations in these tests were the macronutrients nitrogen, phosphorus, and potassium and the micronutrients manganese, iron, copper, zinc, boron, molybdenum, and magnesium. The combinations of nutrient elements were: nitrogen alone (N), phosphorus and potassium (PK), nitrogen, phosphorus and potassium (NPK), and nitrogen, phosphorus, potassium, and micronutrients (NPK+).

Several materials were used as sources of nutrient elements. Ammonium nitrate (33.5-0-0), urea (45-0-0), ammonium sulfate (21-0-0), and ureaform (38-0-0) were used as sources of nitrogen. When the dry form of NPK was needed, a commercial 10-10-10 or 12-12-12 farm fertilizer was used. When an NPK solution was required, a commercial water soluble 23-19-17 fertilizer *(Ra-Pid-Gro*[1]*)* was used. The source materials in *Ra-Pid-Gro* are urea, ammonuim phosphate, potassium phosphate, and potassium nitrate. When P and K were used together in dry form, triple superphosphate (0-45-0) and muriate of potash (0-0-60) were mixed. For the soluble PK treatments, the source material was potassium mono-H phosphate (K_2HPO_4). The combination of micronutrients used was that of *Peters Trace Element Mix*[2], which contains micronutrients as follows (percentages): Mn 9.0, Fe 6.0, Cu 3.0, Zn 3.0, B 2.0, Mo 0.5, and Mg 0.4.

The quantity of nutrient elements per unit area of soil was constant throughout the tests at all five sites regardless of tree size, tree species, tree spacing, or soil type. (The one exception was the rate of nitrogen test on white ash at the Morton Arboretum.) The nitrogen fertilizers were applied at the rate of 29.3 g of elemental N per square meter (6 lb N per 1,000 sq ft). The phosphate fertilizers were applied at 12.9 g of elemental P per square meter (6 lb P_2O_5 per 1,000 sq ft). The potassium fertilizers were applied at 24.3 g of elemental K per square meter (6 lb K_2O per 1,000 sq ft). The amounts of fertilizer source materials used in the soil treatments are given in Table 4.

Foliar fertilization was tested only at the Morton Arboretum. The three water-soluble nutrient sprays applied to the foliage included nitrogen alone, NPK, and NPK plus micronutrients. The amounts of fertilizer source materials used in the foliar treatments are given in Table 5.

Fertilizers were applied to the soil by three methods: (i) broadcast on the soil around the trees, (ii) placed as dry fertilizers into holes made in the soil, and

[1] Ra-Pid-Gro Corporation, Danville, New York
[2] Robert B. Peters Co., Inc., Allentown, Pennsylvania

Table 4. — Nutrient source materials used to fertilize the soil, and rates of usage at the five fertilizer test sites.

Source Material	*Rate of Usage, g/sq m*	*Elemental Nutrients, g/sq m*
Ammonium nitrate (33.5–0–0)	87.4	29.3 N
Ammonium sulfate (21–0–0)	139.5	29.3 N
Urea (45–0–0)	65.1	29.3 N
Ureaform (38–0–0)	77.1	29.3 N
Triple superphosphate (0–45–0)	65.1	12.9 P
Muriate of potash (0–0–60)	49.9	24.3 K
Potassium mono-H-phosphate	58.6	10.4 P, 26.3 K
Commercial 10–10–10	293.2	29.3 N, 12.9 P, 24.3 K
Commercial 12–12–12	244.3	29.3 N, 12.9 P, 24.3 K
Water soluble 23–19–17	127.6	29.3 N, 10.7 P, 18.0 K
Trace element mix	9.1	0.8 Mn, 0.5 Fe, 0.3 Cu, 0.3 Zn, 0.2 B, 0.1 Mo, 0.1 Mg

Table 5. — Nutrient source materials used in foliar fertilization tests, and rates of usage at the Morton Arboretum.

Source Material	*Rate of Usage, g/1 water*	*Elemental Nutrients, g/1 water*
Ammonium nitrate (33.5–0–0)	4.11	1.38 N
Urea (45–0–0)	3.06	1.38 N
Water soluble 23–19–17	6.00	1.38 N, .50 P, .85 K
Trace element mix	.90	.08 Mn, .05 Fe, .03 Cu, .03 Zn, .02 B, .01 Mo, .01 Mg

(iii) injected as fertilizer solutions into the soil.

In the surface broadcasting method, first the area to be fertilized was measured and the size determined. The fertilizer to be used in this area was weighed and distributed uniformly. In the experimental plots at the Morton Arboretum the trees were spaced far enough apart so that they were treated individually. The treated area around a tree was circular with a radius of 1.7 m (5½ ft) and an area of 9.3 sq m (100 sq ft). The fertilizer was broadcast by hand. In all multiple-tree plots the materials were distributed by machine. The wheeled lawn spreader (Fig. 2) was used at Urbana where the trees were growing in plots that had bluegrass turf. The cyclone type spreader (Fig. 3) was used at all other sites.

Where dry fertilizer was placed in holes in the soil the plots were also measured, their areas determined, and the fertilizer weighed. Holes were either drilled in the soil with an auger and an electric drill (Fig. 4) or formed by punching with a soil profile tube (Fig. 5) or punch bar (Fig. 6). The holes were usually drilled when the soil was dry and punched when the soil was moist. In the single-tree plots in the experimental area at the Morton Arboretum the holes were made in a circular pattern with two circles around each tree and a spacing distance of 0.6 m (2 ft) between holes. In the multiple-tree plots the holes were placed in straight lines with the holes 0.6 m apart in the row and the rows 0.6 m apart. Each hole was 30–40 cm (12–15 in) deep. The volume of fertilizer required for 0.36 sq m (4 sq ft) was placed in each hole using a glass beaker. No effort

Fig. 2. — The push-type lawn spreader was used to apply bands of fertilizer alongside rows of trees at Urbana.

Fig. 3. — The cyclone type lawn spreader was used to apply fertilizer to the soil surface at Lisle, Oregon, Marshall, and Carterville.

was made to fill or close the holes following the distribution of the fertilizer.

Injection of liquid fertilizers into the soil was tested in the single-tree plots at the Morton Arboretum. Enough fertilizer solution to treat 15 trees was prepared. Fifty-seven liters (15 gal) of solution were used per tree with this volume evenly divided into 14 injection sites. It was injected 45–60 cm (18–24 in) deep with a soil needle (Fig. 7) and a

Fig. 4. — The electric drill with a soil auger was used to prepare holes in the soil at Lisle.

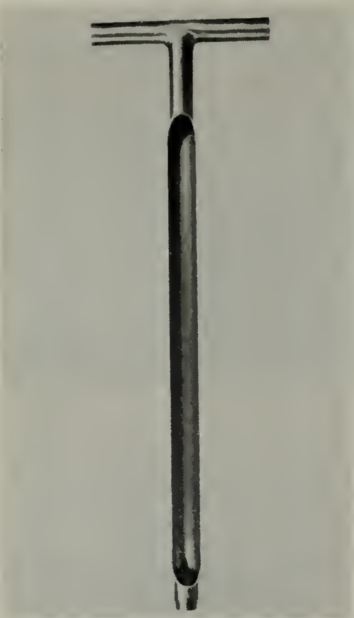

Fig. 5. — The soil profile tube which removes cores of soil from the upper 10–14 inches of soil was used to make holes in the soil at Lisle.

hydraulic sprayer with an agitator using 10 kg per sq cm (150 lb per sq in) pressure. The volume of fertilizer used at each injection site was regulated by opening the soil needle valve for a predetermined number of seconds. Four of the injections were made on the four sides of the tree approximately 0.75 m from the tree trunk and the remaining ten injections were made in a circle approximately 1.4 m from the trunk.

Foliar fertilization was tested on the single-tree plots at the Morton Arboretum. Fertilizer solutions were prepared in amounts to treat 15 trees. The quantities of nutrients applied per tree in foliar treatments were much less than the quantities used in soil applications. The trees were sprayed with a hydraulic sprayer until the solution began to drip from the foliage. No attempt was made to prevent runoff onto the soil. Foliar sprays were applied each year during May, June, and July at approximately monthly intervals. They were applied between 8 A.M. and 12 noon on days having little or no wind. Each tree received 6–8 liters of solution each application.

In all of the fertilizer tests the growth responses were determined by measuring the tree trunks approximately 1 m above the soil. The circumference of each tree was measured with a steel tape at the start of each test and at the end of each growing season. Trees were measured to the nearest 0.005 ft (1.5 mm) in circumference. The height at which the trunk was measured was permanently marked with tree marking paint or with a nail at one or more points around the tree.

The following sections present specific information concerning the different fertilizer tests at the five sites.

Morton Arboretum

With one exception the trees at the Morton Arboretum were in two areas—the experimental area, which is along the northern boundary of the Arboretum and was once pasture, and the forestry plots, which are in the approximate center of the Arboretum and are surrounded by a natural stand of forest trees. The exception was a natural stand of large white oaks immediately adjacent to the experimental area.

The three species growing in the experimental area were pin oak, white ash, and honey locust. They had been planted in square blocks with 4.5 or 6.0 m spacing distances between trees and 7.5 m between blocks. Each block contained 100 trees of a single species. The oaks and ashes were planted in 1956, and the locusts in 1957. When planted, the oaks were 0.3–1.0 m tall, the ashes 1.3–2.0 m tall, and the locusts 1.0–1.3 m tall. All blocks had been

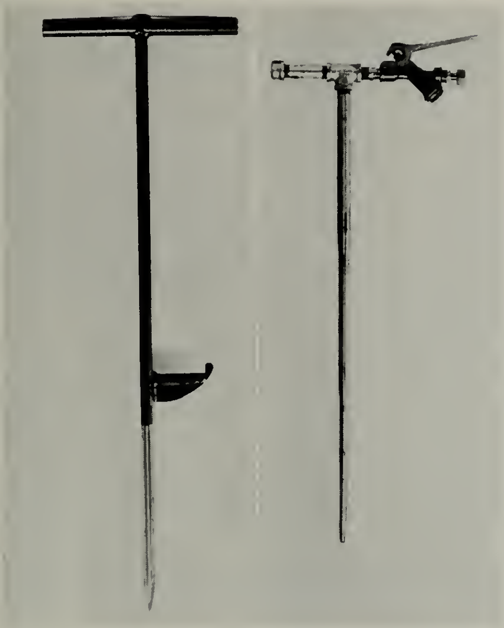

Fig. 6. — A punch bar made from a car axle was used to prepare holes in the soil at Lisle, Oregon, Marshall, and Carterville (left).

Fig. 7. — A soil needle attached to a hydraulic pump with a hose was used to inject water-soluble fertilizers into the soil at Lisle.

planted with Kentucky bluegrass, *Poa pratensis* L., and a sod was maintained with occasional mowing each summer.

White ash, pin oak, and honey locust trees were used in a *method* test. Each block of trees was divided into plots. Each plot contained five contiguous trees and received one of 16 treatments. Eighty trees of each species were treated. Several trees (14 oak, 12 ash, and 10 locust) received no treatment and served as controls.

The 16 treatments included ammonium nitrate and urea each applied dry to the soil on the surface and in holes, in the soil in solution, and as a spray to the tree foliage; NPK and NPK plus micronutrients applied to the soil in holes and in solution and to the tree foilage; and PK applied to the soil in holes and in solution.

The treatment each tree received in 1963 was repeated in 1964 and 1965. Soil treatments were made on May 14, 15, and 16, 1963; on April 22 and 23, 1964; and on April 28 and 29, 1965. Foliage treatments were made on May 6, June 20, and July 23, 1963; on May 20, June 24, and July 24, 1964; and on May 18, June 9, and July 15, 1965.

Annual growth of the trees was measured for 6 years. The initial measurement was made on May 13, 1963 and the subsequent growth measurements were made on October 2, 1963, October 7, 1964, October 14, 1965, September 28, 1966, October 19, 1967, and October 16, 1968.

One block of pin oaks in the experimental area was used in a *time of application* test. Sixteen treatments were used, each treatment applied to five trees selected at random. Ten trees were untreated and served as controls.

In all treatments nitrogen fertilizers were applied to the soil surface. The nitrogen fertilizer source materials were ammonium nitrate, ammonium sulfate, urea, and ureaform. Each tree received 29.3 g of elemental N per square meter (6 lb per 1,000 sq ft) per year. Each source material was applied (i) full rate in April; (ii) ½ rate in April and ½ rate in June; (iii) ⅓ rate in April, ⅓ rate in June, and ⅓ rate in October; or (iv) full rate in October. Each tree received the same treatment for 3 consecutive years; on April 23, June 24, and October 6, 1964; April 27, June 9, and October 14, 1965; and April 26, June 8, and September 27, 1966.

Annual growth was measured for five seasons. The initial tree measurement was made on May 7, 1964 and growth measurements were made on the same days as those reported above for the *method* test.

One block of white ash trees in the experimental area was used in a *rate of application* test. Each tree was treated individually with a random selection for treatment throughout the block. There were 16 treatments with each treatment applied to five trees. Fifteen trees were untreated and served as controls.

All treatments were nitrogen fertilizers applied to the soil surface. The nitrogen source materials were ammonium nitrate, ammonium sulfate, urea, and ureaform. The rates of application were ½, 1, 1½, and 2 times the rates shown in Table 4. Fertilizers were applied on April 22, 1964 and April 27, 1965, each tree receiving the same treatment for 2 consecutive years.

Annual growth was measured for 4 years. The initial trunk measurements were made on April 22, 1964 and subsequent measurements were made on October 7, 1964, October 14, 1965, September 28, 1966, and October 19, 1967.

The remaining fertilizer test at the Morton Arboretum was the *species response* test. The trees in this test (with the exception of the white oaks) were in the forestry plots. They were crowded, relatively small, 40-year-old trees. Relatively uniform groups of approximately 20 trees of each of six species were selected for the test.

Table 6. — Tree species, fertilizer treatments, and fertilizer amounts used per year in species response tests at the Morton Arboretum.

Tree Species	*Treatment*[a]	*Number Trees in Plot*	*Plot Dimensions, m*	*Plot Area, sq m*	*Amount of Fertilizer Used, kg*
Basswood	N surface	9	14.6 x 12.2	178	15.6
	None	9			
Norway maple	N surface	10	22.0 x 9.8	216	18.8
	None	10			
Red maple	N surface	10	14.6 x 9.8	143	12.5
	None	11			
Sugar maple	N surface	11	20.1 x 7.3	147	12.8
	None	11			
Red oak	N surface	10	14.6 x 12.2	178	15.6
	None	12			
Swamp white oak	N surface	12	19.5 x 12.2	240	20.8
	None	11			
White oak	N surface	12	30.5 x 29.4	897	78.4
	None	11			

[a] Ammonium nitrate.

The area was divided into two plots. Ammonium nitrate was broadcast over the soil surface of one plot. The other plot served as an unfertilized control. Plot sizes and fertilizer amounts are given in Table 6. The trees were treated for 3 consecutive years, on April 20, 1964, April 27, 1965, and April 26, 1966.

Initial tree measurements were made on April 20, 1964 and annual growth measurements were made on October 7, 1964, October 14, 1965, September 28, 1966, and October 10, 1967.

Natural History Survey Arboretum

The test in the Natural History Survey arboretum was a *species response* test in a field that had previously been cultivated. The trees were planted, in nursery-type rows, 2 or 3 years before the test began and were just becoming established. A lawn-type bluegrass sod was present.

Ammonium nitrate was applied in 0.6-m wide bands to the soil surface along each side of rows of five species of trees. Alternating 5-tree plots in a row were treated or left untreated with one border tree between plots. No adjacent rows were treated. The trees were treated for 3 consecutive years, on April 16, 1964, May 13, 1965, and May 10, 1966. The amounts of fertilizer applied are given in Table 7. Initial tree measurements were made on May 8, 1964, and the growth measurements were taken on October 12, 1964, October 5, 1965, and October 5, 1966.

Sinnissippi Forest

At Sinnissippi Forest the test plots were in plantations established in open fields that once were farmed. The green ash and sycamore plots were in experimental plantations of approximately 0.4 hectare (1 acre). The red pine and black walnut were in larger plantations. In the ash and pine plantations shading restricted the growth of competing vegetation. Weeds were present in the sycamore and walnut plantations. Each species was divided plots of 10–12 trees with one, two, or more rows of trees separating the plots.

This *method* test compared (i) nitrogen on the surface, (ii) NPK on the surface, (iii) NPK in soil holes, and (iv) no treatment. The ashes received an additional treatment of PK on the surface. The fertilizer treatments and the amounts applied are given in Table 8. The plots were treated on May 5 and 6, 1965, April 28, 1966, and April 18, 1967.

Initial tree measurements were made

Table 7. — Tree species, fertilizer treatments, and fertilizer amounts used per year in species response tests at the Natural History Survey arboretum.

Tree Species	*Treatment*[a]	*Number Trees in Plot*	*Plot Dimensions, m*	*Plot Area, sq m*	*Amount of Fertilizer Used, kg*
Green ash	N surface	8	16.8 x 1.2	20	1.8
	None	9			
Chinese elm	N surface	14	24.4 x 1.2	29	2.6
	None	10			
Hawthorn	N surface	14	24.4 x 1.2	29	2.6
	None	11			
Littleleaf linden	N surface	12	24.4 x 1.2	29	2.6
	None	9			
Norway maple	N surface	20	32.0 x 1.2	38	3.4
	None	19			

[a] Ammonium nitrate.

Table 8. — Tree species, fertilizer treatments, and fertilizer amounts used per year in method tests at Sinnissippi Forest.

Tree Species	*Treatment*	*Source Material*	*Number Trees in Plot*	*Plot Dimensions, m*	*Plot Area, sq m*	*Amount of Fertilizer Used, kg*
Green ash	N surface	Ammonium nitrate	10	12.2 x 9.8	120	10.5
	PK surface	Potassium phosphate	9	17.1 x 9.8	168	9.8
	NPK surface	12–12–12	10	14.6 x 9.8	143	34.9
	NPK holes	12–12–12	10	12.2 x 9.8	120	29.3
	None		12			
Red pine	N surface	Ammonium nitrate	12	10.4 x 8.5	88	7.7
	NPK surface	12–12–12	12	10.4 x 8.5	88	21.5
	NPK holes	12–12–12	12	10.4 x 8.5	88	21.5
	None		12			
Sycamore	N surface	Ammonium nitrate	10	14.6 x 9.8	143	12.5
	NPK surface	12–12–12	10	14.6 x 9.8	143	34.9
	NPK holes	12–12–12	10	12.2 x 9.8	120	29.3
	None		11			
Black walnut	N surface	Ammonium nitrate	11	12.2 x 9.8	120	10.5
	NPK surface	12–12–12	10	12.2 x 8.5	104	25.4
	NPK holes	12–12–12	10	14.6 x 7.6	111	27.1
	None		10			

on May 6, 1965 and subsequent growth measurements were made on September 17, 1965, September 15, 1966, October 20, 1967, and October 10, 1968.

Lincoln Trail State Park

The *method* test at Lincoln Trail State Park was similar in scope and design to that at Sinnissippi Forest. The sweet

Table 9. — Tree species, fertilizer treatments, and fertilizer amounts used per year in method tests at Lincoln Trail State Park.

Tree Species	*Treatment*	*Source Material*	*Number Trees in Plot*	*Plot Dimensions, m*	*Plot Area, sq m*	*Amount of Fertilizer Used, kg*
Loblolly pine	N surface	Urea	7	9.2 x 7.3	67	4.4
	NPK surface	12–12–12	6	17.4 x 3.7	64	15.6
	None		6			
Persimmon	N surface	Urea	8	11.0 x 5.5	61	4.0
	NPK surface	12–12–12	7	14.0 x 5.2	73	17.8
	None		8			
Sweet gum	N surface	Urea	12	10.1 x 9.2	93	6.1
	NPK surface	12–12–12	12	9.2 x 8.2	75	18.3
	NPK holes	12–12–12	12	9.2 x 8.2	75	18.3
	None		13			
Sycamore	N surface	Urea	7	17.4 x 5.5	96	6.2
	NPK surface	12–12–12	8	19.2 x 3.7	71	17.3
	NPK holes	12–12–12	7	10.7 x 7.3	78	19.1
	None		8			
Tulip tree	N surface	Urea	10	12.8 x 8.2	105	6.8
	NPK surface	12–12–12	10	11.0 x 11.0	121	29.6
	NPK holes	12–12–12	10	20.1 x 3.7	74	18.1
	None		9			

Table 10. — Tree species, fertilizer treatments, and fertilizer amounts used per year in species response tests at Crab Orchard National Wildlife Refuge.

Tree Species	*Treatment*	*Source Material*	*Number Trees in Plot*	*Plot Dimensions, m*	*Plot Area, sq m*	*Amount of Fertilizer Used, kg*
Sweet gum	N surface	Urea	19	11.0 x 6.4	70	4.6
	NPK surface	12-12-12	21	11.0 x 9.1	100	24.4
	NPK holes	12-12-12	17	11.0 x 7.3	80	19.5
	None		21			
Pecan	N surface	Urea	1 [a]	9.6 x 9.6	92	6.0
	NPK surface	12-12-12	1 [a]	9.6 x 9.6	92	22.5
	None		1 [a]			
Black Walnut	N surface	Urea	11	23.8 x 11.9	283	18.4
	NPK surface	12-12-12	15	23.8 x 11.9	283	69.0
	None		12			

[a] 10 single tree plots used.

gum, sycamore, tulip tree, and loblolly pine trees were in approximately 0.1-hectare (¼ acre) plantations. The persimmon trees were in a natural stand. Weeds were present in all plots at Lincoln Trail. The treatments and fertilizer amounts used are given in Table 9. The trees were treated on April 21, 1966, April 12, 1967, and March 28, 1968.

Initial tree measurements were made April 21, 1966 and subsequent measurements were made on September 2, 1966, October 10, 1967, and September 26, 1968.

Crab Orchard Wildlife Refuge

The tree plots at Crab Orchard Refuge, with the exception of the pecans, were less uniform than the tree plots at the other four sites. The pecan trees were widely separated in an orchard and were treated as single-tree plots. The sweet gums were in a very closely spaced plantation. Many weakened and dead trees were cut off at the ground line and removed from the plots at the time of the first treatment. The walnut trees were in a natural stand of approximately 0.4 hectare (1 acre). Sugar maples that were competing with the walnuts were killed with 2,4,5-T in 1966. The treatments and fertilizer amounts used at Crab Orchard Refuge are given in Table 10.

The sweet gums and pecans were treated on April 12 and 13, in 1966 and 1967, and April 3 and 4 in 1968. They were first measured on April 13, 1966. The walnuts were treated on April 18, 1967 and April 4, 1968 and were first measured on April 18, 1967. The growth measurements were made on September 2, 1966, September 6, 1967, and September 19, 1968.

RESULTS

The responses to fertilizer applications in this study were measured through comparisons of the annual trunk growth of each tree. The annual growth was calculated from circumference measurements of the trees usually made during the month of October.

Morton Arboretum

The responses to fertilization of pin oak, white ash, and honey locust in the experimental area of the Morton Arboretum were consistent and significant throughout the study. As with all biological data, there were variations between trees, plots, treatments, species, and years during the testing period.

The annual growth determinations in the *method* test are given in tabular form—the pin oak data in Table 11, the white ash data in Table 12, and the

Table 11.—Trunk diameter growth of pin oaks in the method-of-application fertilizer plot at the Morton Arboretum. Five trees per treatment were fertilized in 1963, 1964, and 1965.

Plot	*Nutrient*	*Method of Application*	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm*					
				1963	1964	1965	1966	1967	1968
1	N [a]	Soil surface	3.70	1.23	1.51	2.14	1.34	1.25	1.24
2	N [a]	Soil holes	4.28	1.31	1.68	2.18	1.28	1.38	1.02
3	N [a]	Soil solution	4.18	1.41	1.67	2.05	1.15	1.22	1.01
4	N [a]	Foliar	4.68	0.89	1.31	1.71	1.12	1.34	0.95
5	N [b]	Soil surface	3.99	1.25	1.60	1.92	1.11	1.19	0.87
6	N [b]	Soil holes	4.72	1.27	1.71	1.89	1.42	1.47	1.18
7	N [b]	Soil solution	4.22	1.17	1.48	1.95	1.14	1.53	1.20
8	N [b]	Foliar	3.76	0.90	1.13	1.27	0.94	1.29	1.25
9	PK	Soil holes	4.27	0.88	1.14	1.18	0.97	1.43	1.19
10	PK	Soil solution	3.85	0.87	1.09	1.24	0.98	1.24	1.04
11	NPK	Soil holes	3.63	1.06	1.56	1.84	1.16	1.42	1.02
12	NPK	Soil solution	3.74	1.61	1.97	2.31	1.33	1.34	1.28
13	NPK	Foliar	4.35	0.80	1.18	1.62	1.10	1.42	1.22
14	NPK+ [c]	Soil holes	4.42	1.04	1.94	2.24	1.50	1.60	1.43
15	NPK+ [c]	Soil solution	3.78	1.23	1.61	2.06	1.13	1.13	0.90
16	NPK+ [c]	Foliar	3.70	0.67	1.16	1.51	0.98	1.40	1.48
Check	None	....	3.76	0.81	1.14	1.29	1.07	1.31	1.24

[a] Ammonium nitrate.
[b] Urea.
[c] NPK + micronutrient mixture.

Table 12.—Trunk diameter growth of white ashes in the method-of-application fertilizer plot at the Morton Arboretum. Five trees per treatment were fertilized in 1963, 1964, and 1965.

Plot	*Nutrient*	*Method of Application*	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm*					
				1963	1964	1965	1966	1967	1968
1	N [a]	Soil surface	9.82	1.28	1.25	1.56	1.19	1.13	0.92
2	N [a]	Soil holes	8.43	0.89	1.15	1.41	1.13	1.08	0.74
3	N [a]	Soil solution	7.02	0.98	1.04	1.22	0.91	0.74	0.63
4	N [a]	Foliar	8.26	1.01	0.83	0.85	0.95	0.96	0.75
5	N [b]	Soil surface	7.21	0.92	1.05	1.02	1.01	0.76	0.72
6	N [b]	Soil holes	7.75	1.00	1.07	1.42	1.18	1.10	0.79
7	N [b]	Soil solution	7.00	1.26	1.39	1.69	1.38	1.26	1.03
8	N [b]	Foliar	7.37	1.05	0.87	1.16	1.15	1.27	0.91
9	PK	Soil holes	7.62	0.80	0.81	0.87	0.92	0.95	0.79
10	PK	Soil solution	6.80	0.69	0.68	0.87	0.79	0.87	0.76
11	NPK	Soil holes	8.62	1.05	1.06	1.36	1.01	1.05	0.85
12	NPK	Soil solution	7.95	1.23	1.36	1.54	1.21	1.01	0.84
13	NPK	Foliar	7.48	0.78	0.68	0.93	0.91	0.81	0.63
14	NPK+ [c]	Soil holes	8.20	0.94	1.13	1.28	1.20	1.06	0.90
15	NPK+ [c]	Soil solution	8.57	1.06	1.17	1.36	1.19	1.17	0.69
16	NPK+ [c]	Foliar	8.06	0.94	1.00	1.40	1.23	1.32	0.93
Check	None	....	8.06	0.85	0.76	0.92	0.97	1.00	0.88

[a] Ammonium nitrate.
[b] Urea.
[c] NPK + micronutrient mixture.

honey locust data in Table 13. A more condensed and digested version of the data from the 3 species is presented in Table 14, showing the percentage increases of treated over untreated trees.

RESPONSE TO METHOD OF APPLICATION.—Nutrients applied to the foliage of trees stimulated growth much less than soil-applied nutrients. Trees receiving foliar applications grew slightly more or no more than the trees receiving no treatment. The oak and ash trees that received foliar nutrients grew more than untreated trees, while the treated honey locusts grew less than untreated trees (Table 14). The differences in growth between untreated trees and foliar-treated trees were probably due to plot variability rather than treatment response. Statistically, the results from foliar treatments were not significantly better than the results from no treatment (Himelick, Neely, & Crowley 1965). Stimulation of growth, if present, may have resulted, in part, from the uptake of nutrients that dripped from the foliage onto the soil.

All methods of applying fertilizer to the soil stimulated tree growth. Neither surface application, dry fertilizer in soil holes, nor injection of soluble fertilizers into the soil was significantly better than any other soil application method, while all three produced significantly better growth than occurred with foliar fertilization and in untreated controls. Minor variations in growth response did occur between the three soil methods of fertilization. During the 3 years fertilizers were applied, the locusts responded best to surface applications, and the oaks and ashes responded best to solution injection (Table 14). The method of placing dry fertilizers in soil holes was slightly less effective than the other soil methods. Trees treated in this manner, however, tended to show more of a residual response the year following treatment than trees fertilized by surface application or solution injection.

RESPONSE TO NUTRIENTS.—In this test on oak, ash, and locust trees, there was no positive growth response to fertilization with phosphorus and potas-

Table 13.—Trunk diameter growth of honey locusts in the method-of-application fertilizer plot at the Morton Arboretum. Five trees per treatment were fertilized in 1963, 1964, and 1965.

Plot	Nutrient	Method of Application	Average Initial Diameter, cm	Trunk Diameter Growth, cm					
				1963	1964	1965	1966	1967	1968
1	N [a]	Soil surface	5.01	1.35	1.61	1.65	1.23	1.35	1.33
2	N [a]	Soil holes	4.06	0.78	1.13	1.46	1.00	1.32	0.99
3	N [a]	Soil solution	4.26	1.19	1.71	1.92	1.50	1.86	1.81
4	N [a]	Foliar	3.86	0.61	0.54	0.88	0.77	1.11	0.98
5	N [b]	Soil surface	4.19	1.24	1.44	1.64	0.97	1.11	1.15
6	N [b]	Soil holes	3.64	0.63	0.94	1.33	0.98	0.90	0.75
7	N [b]	Soil solution	4.17	1.08	1.33	1.72	1.01	1.04	0.83
8	N [b]	Foliar	3.12	0.54	0.53	0.79	0.59	0.78	0.63
9	PK	Soil holes	4.58	0.55	0.65	0.76	0.71	0.89	0.83
10	PK	Soil solution	4.89	0.58	0.53	0.83	0.71	0.96	0.76
11	NPK	Soil holes	3.91	0.77	0.92	1.34	0.78	0.86	0.77
12	NPK	Soil solution	3.79	0.83	0.99	1.33	0.86	0.95	0.91
13	NPK	Foliar	3.87	0.50	0.52	0.72	0.72	0.87	0.86
14	NPK+ [c]	Soil holes	4.62	0.72	0.97	1.28	0.92	0.93	0.80
15	NPK+ [c]	Soil solution	5.39	1.03	1.15	1.41	0.93	1.12	1.06
16	NPK+ [c]	Foliar	4.82	0.54	0.50	0.61	0.75	1.20	1.00
Check	None	....	5.02	0.66	0.64	0.92	0.86	1.10	1.08

[a] Ammonium nitrate.
[b] Urea.
[c] NPK + micronutrient mixture.

Table 14. — Percent annual trunk diameter growth increase of treated trees over that of untreated trees in the method-of-application fertilizer plots in the Morton Arboretum. Trees were fertilized in 1963, 1964, and 1965.

Species	Year	Percent Growth Increase Over Untreated Trees								
		Method of Application				Nutrients				
		Surface	Holes	Solution	Foliar	N[a]	N[b]	PK	NPK	NPK+[c]
Oak	1963	53	44	68	1	63	52	9	64	41
	1964	37	51	47	5	42	40	—2	55	56
	1965	57	58	62	19	64	49	—6	61	67
	1966	15	25	11	—3	18	14	—8	17	23
	1967	—7	12	0	4	—2	7	2	5	4
	1968	—15	—6	—11	—1	—12	—13	—10	—7	—6
Ash	1963	29	14	33	12	24	25	—12	34	18
	1964	51	45	63	12	51	54	—1	59	51
	1965	40	49	58	18	52	50	—5	58	43
	1966	13	16	21	9	11	23	—11	14	24
	1967	—5	7	7	9	—2	4	—9	8	12
	1968	—7	—7	—9	—8	—14	—3	—11	—3	—9
Locust	1963	97	11	56	—17	68	48	—14	21	33
	1964	139	55	103	—19	131	94	—8	50	66
	1965	79	47	74	—18	83	70	—13	46	47
	1966	28	7	26	—17	44	15	—17	—5	8
	1967	12	—9	13	—10	37	—7	—15	—16	—6
	1968	15	—23	6	—19	28	—16	—26	—22	—14

[a] Ammonium nitrate.
[b] Urea.
[c] NPK + micronutrient mixture.

sium (PK). Trees treated with PK alone grew less in almost every instance than untreated trees. Retarding of growth by 5–15 percent was common (Table 14).

The addition of PK to nitrogen fertilizers neither significantly stimulated growth nor retarded growth when compared with the results of applications of nitrogen alone. There was some variation between plots of the three species. During 1963, 1964, and 1965, oaks treated with NPK grew more than those treated with N, whereas locusts treated with NPK grew less than those treated with N. Ashes treated with NPK and N grew approximately the same amount (Table 14).

The oak, ash, and locust trees did not respond to applications of the micronutrient mixture. Of the 27 paired comparisons that can be made from 1963, 1964, and 1965 data in Tables 11, 12, and 13 between plots that received micronutrients and plots that did not, the trees in 10 plots grew more with micronutrients while in the remaining 17 plots the trees grew more without micronutrients.

Nitrogen was the only nutrient that stimulated growth of trees in almost every instance when it was applied to the soil. Nitrogen alone or nitrogen with other nutrients gave approximately the same growth response. During the 3 years the trees were fertilized, the nitrogen source materials stimulated 52 percent increased growth on pin oak, 43 percent on white ash, and 82 percent on honey locust trees.

Pin oaks grew more in 1964 than in 1963 and more in 1965 than in 1964 (Table 11). This increased growth occurred in both treated and untreated trees. The percentages of increased growth of treated over untreated trees, however, do not show this regular pattern (Table 14). This indicates that the increased growth in 1964 and 1965 was due to climatic factors and not to residual nutrients remaining available from treatments in previous years.

Increased growth of the fertilized trees persisted for only 1 or 2 years after fertilization ceased. In 1968, the third year after fertilization ceased, the treated trees grew less than the untreated trees (Table 14). Competition for light, water, or nutrients between trees in the fertilized plots may have limited the growth in 1967 and 1968. The branches between trees in many of the fertilized plots began to touch in 1967, and this was not true in the untreated plots.

RESPONSE TO TIME OF APPLICATION.—Data for comparing the effect of fertilizing trees during different seasons of the year were derived from one block of pin oaks treated with surface application of four nitrogen fertilizers. The annual growth measurements of trees treated at the various seasons are given in Table 15. A summary of this data expressed as percentage increases in growth of treated over untreated trees is given in Table 16.

The greatest growth stimulation was obtained by applying all of the nitrogen in April. Trees receiving a portion or all of the nitrogen in June or October grew less than trees receiving all of the nitrogen in April. Trees fertilized in October grew more than untreated trees.

Unfortunately, the trees treated in October were at a disadvantage in two ways. They were not fertilized in October of 1963; therefore, all fertilizers were not available during the same growing seasons. Also, the fertilized pin oaks were competing for space during 1966 and this factor may have limited the increased response to fertilizers during 1966 and subsequent years. Trees fertilized in April and June responded well to fertilizers in 1964 and 1965, while trees fertilized in October responded well only in 1965 (Table 16).

RESPONSE TO RATE OF APPLICATION.—Data for comparing the response to varying rates of application of nitrogen fertilizers were obtained from one block of white ash trees treated with surface applications of four nitrogen fertilizers. The growth measurements of the trees are given in Table 17.

Data from this test, although more variable than data from previously dis-

Table 15.—Trunk diameter growth of pin oaks in the time-of-application fertilizer plot at the Morton Arboretum. Five trees per treatment were fertilized in 1964, 1965, and 1966.

Plot	Season of Application	Nitrogen Source	Rate of N Each Application, g/sq m	Average Initial Diameter, cm	Trunk Diameter Growth, cm 1964	1965	1966	1967	1968
1	April	N[a]	29.3	4.97	1.34	1.81	1.41	1.44	1.38
2	"	N[b]	29.3	5.37	1.74	2.11	1.48	1.48	1.32
3	"	N[c]	29.3	6.14	1.55	2.13	1.35	1.40	1.32
4	"	N[d]	29.3	5.57	0.97	1.66	1.40	1.55	1.63
5	April, June	N[a]	14.7	5.03	1.24	2.10	1.66	1.34	1.36
6	"	N[b]	14.7	5.85	1.28	1.93	1.59	1.54	1.37
7	"	N[c]	14.7	5.67	1.07	1.63	1.31	1.30	1.09
8	"	N[d]	14.7	5.12	0.95	1.53	1.31	1.30	1.22
9	April, June, Oct.	N[a]	9.8	4.92	1.04	1.61	1.26	1.27	1.15
10	"	N[b]	9.8	5.63	1.29	2.13	1.45	1.66	1.45
11	"	N[c]	9.8	5.18	1.18	1.86	1.43	1.51	1.47
12	"	N[d]	9.8	5.63	1.14	1.60	1.35	1.47	1.51
13	October	N[a]	29.3	4.97	0.86	1.62	1.31	1.51	1.47
14	"	N[b]	29.3	4.86	0.88	1.73	1.35	1.47	1.34
15	"	N[c]	29.3	4.19	0.80	1.37	1.07	1.12	1.19
16	"	N[d]	29.3	5.10	0.94	1.49	1.31	1.55	1.45
Check		None	....	5.37	0.89	1.26	1.23	1.36	1.27

[a] Ammonium nitrate.
[b] Ammonium sulfate.
[c] Urea.
[d] Ureaform.

Table 16. — Percent annual trunk diameter growth increase of treated trees over that of untreated trees in the pin oak time-of-application fertilizer plot in the Morton Arboretum. Trees were fertilized in 1964, 1965, and 1966.

	Percent Growth Increase Over Untreated Trees							
	Season of Application				Nitrogen Source			
Year	April	April June	April June October	October	Ammonium Nitrate	Ammonium Sulfate	Urea	Ureaform
1964	57	28	30	—2	26	46	29	12
1965	53	43	43	23	42	57	39	25
1966	15	19	11	2	15	19	5	9
1967	8	1	9	4	2	13	—2	8
1968	11	—1	10	7	6	8	0	14

Table 17. — Trunk diameter growth of white ashes in 1964 and 1965 in the rate-of-application fertilizer plot at the Morton Arboretum. Five trees per treatment were fertilized in 1964 and 1965.

	Trunk Diameter Growth, cm					*Percent Increase Over Untreated*
Rate of N, g/sq m	Ammonium Nitrate	Ammonium Sulfate	Urea	Ureaform	*Av.*	
14.7	2.37	1.83	1.83	1.67	*1.93*	15
29.3	3.28	2.32	2.13	2.02	*2.44*	45
44.0	2.24	2.41	2.35	2.88	*2.47*	47
58.6	2.46	2.84	2.88	2.30	*2.62*	56

cussed tests, clearly indicate that as more nitrogen is applied to the soil more growth will result. At 14.7 g per sq m, growth was increased 15 percent; at 29.3 g, growth was increased 45 percent; at 44.0 g, growth was increased 47 percent; and at 58.6 g, growth was increased 56 percent above that of untreated controls. These treatments caused no injury to turf or trees.

RESPONSE TO SOURCE OF NITROGEN. —Data used in comparing the source materials for nitrogen were obtained in the tests on *method of application* (Tables 11, 12, 13, 14), *time of application* (Tables 15, 16), and *rate of application* (Table 17). There was little difference in growth response to the four nitrogen source materials used. On oaks, ammonium nitrate was slightly more effective than urea, and ammonium sulfate was slightly more effective than ammonium nitrate. On ash trees, ammonium nitrate, ammonium sulfate, urea, and ureaform gave approximately equal responses. On locusts, ammonium nitrate was slightly more effective than urea. Ureaform releases nitrogen more slowly than the other three materials and tended to produce less growth in the first year of treatment and slightly greater growth in succeeding years.

SPECIES RESPONSE TESTS.—Data on the response of seven species of trees in the Morton Arboretum to nitrogen fertilization came primarily from 30-year-old, crowded, and slow-growing trees. The determinations of annual growth of these trees are given in Table 18.

The increased growth due to fertilization was greatest on swamp white oak, red maple, and red oak (Table 18). The swamp white oaks were the smallest trees of the seven species, were the slowest growing when untreated, and gave the greatest increase in growth

Table 18.—Trunk diameter growth of trees in the species response fertilizer plots at the Morton Arboretum. Trees were fertilized in 1964, 1965, and 1966.

Species	*Treatment*[a]	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm* 1964	1965	1966	1967	*Total*[b]	*Percent Increase Over Untreated*
Basswood	N surface	24.3	0.41	0.58	0.51	0.56	*1.50*	15
	None	24.9	0.36	0.53	0.41	0.48	*1.30*	...
Norway maple	N surface	18.0	0.30	0.41	0.28	0.36	*0.99*	—19
	None	21.0	0.38	0.51	0.33	0.38	*1.22*	...
Red maple	N surface	18.6	0.33	0.48	0.25	0.30	*1.06*	61
	None	17.9	0.18	0.25	0.23	0.23	*0.66*	...
Sugar maple	N surface	17.2	0.25	0.30	0.20	0.30	*0.75*	—1
	None	17.0	0.20	0.33	0.23	0.28	*0.76*	...
Red oak	N surface	16.8	0.28	0.58	0.56	0.51	*1.42*	30
	None	14.2	0.25	0.41	0.43	0.43	*1.09*	...
Swamp white oak	N surface	12.2	0.41	0.51	0.51	0.56	*1.43*	170
	None	12.2	0.10	0.15	0.28	0.25	*0.53*	...
White oak	N surface	44.9	0.25	0.43	0.33	0.46	*1.01*	—17
	None	45.8	0.36	0.48	0.38	0.51	*1.22*	...

[a] Ammonium nitrate.
[b] 1964, 1965, and 1966 data only.

once fertilized. The trees in the fertilized basswood plot also grew more than trees in the unfertilized plot. The trees in the fertilized plots of sugar maple, Norway maple, and white oak grew less than those in the untreated plots.

Competition between the larger trees, sugar maple, Norway maple, and white oak, apparently limited the stimulatory effect that an added supply of plant nutrients often provides. The annual diameter increase of these three species of trees was approximately 0.4 cm. Younger, more widely spaced trees in the *method-of-application* test frequently increased in diameter by 1.2–1.6 cm per year. The plots of sugar maple, Norway maple, and white oak are the only plots of deciduous trees in this study that failed to show increased growth following soil application of nitrogen fertilizers.

Natural History Survey Arboretum

All species of trees at the Natural History Survey arboretum responded positively to fertilization. The average diameter growths of treated and untreated trees are given in Table 19.

Increased growth due to fertilization was 55 percent for hawthorns, 45 percent for lindens, 29 percent for Norway maples, 16 percent for Chinese elms, and 15 percent for green ashes. The trees that showed the slowest growth when untreated, hawthorn and linden, gave the greatest percentage increases in growth when treated. The substantial growth increase in 1965 over that in 1964 for all species except hawthorn was likely a result of favorable climatic conditions. The hawthorns were partially defoliated by the fungus *Entomosporium maculatum* Lev. during the summers of 1965 and 1966, which may have limited the response of this species to fertilization.

Sinnissippi Forest

The three species of deciduous trees at Sinnissippi Forest—green ash, sycamore, and black walnut—all benefited from the application of fertilizers. The amounts of annual diameter growth are given in Table 20. Walnut, the slowest growing species, responded with the greatest percentage growth increase following fertilization. Sycamore, the fastest growing species, responded with the lowest percentage growth increase. The average

Table 19.—Trunk diameter growth of trees in the species response fertilizer plots at the Natural History Survey arboretum. Trees were fertilized in 1964, 1965, and 1966.

Species	*Treatment*[a]	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm* 1964	1965	1966	*Total*	*Percent Increase Over Untreated*
Green ash	N surface	2.4	0.97	1.93	1.50	*4.40*	15
	None	2.8	0.86	1.50	1.45	*3.81*	...
Chinese elm	N surface	1.9	1.73	2.29	1.73	*5.75*	16
	None	2.4	1.47	1.88	1.60	*4.95*	...
Hawthorn	N surface	2.4	0.74	0.66	0.64	*2.04*	55
	None	2.1	0.36	0.48	0.48	*1.32*	...
Littleleaf linden	N surface	1.2	0.28	0.86	1.17	*2.31*	45
	None	1.3	0.25	0.53	0.81	*1.59*	...
Norway maple	N surface	1.7	0.84	1.45	0.84	*3.13*	29
	None	1.7	0.64	1.07	0.71	*2.42*	...

[a] Ammonium nitrate.

Table 20.—Trunk diameter growth of trees in the method-of-treatment fertilizer plots at Sinnissippi Forest. Trees were fertilized in 1965, 1966, and 1967.

Species	*Treatment*	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm* 1965	1966	1967	1968	*Total*[a]	*Percent Increase Over Untreated*
Green ash	N surface	10.5	0.50	0.51	0.77	0.51	*1.78*	65
	PK surface	11.6	0.36	0.29	0.54	0.40	*1.19*	10
	NPK surface	11.4	0.56	0.57	0.90	0.75	*2.03*	88
	NPK holes	11.4	0.43	0.58	0.87	0.63	*1.88*	74
	None	11.3	0.25	0.32	0.51	0.47	*1.08*	...
Red pine	N surface	13.7	0.25	0.08	0.19	0.13	*0.52*	—20
	NPK surface	13.8	0.25	0.09	0.15	0.13	*0.49*	—25
	NPK holes	15.0	0.28	0.16	0.24	0.26	*0.68*	5
	None	13.8	0.24	0.17	0.24	0.32	*0.65*	...
Sycamore	N surface	12.1	0.58	0.39	0.50	0.41	*1.47*	11
	NPK surface	10.5	0.75	0.49	0.83	0.50	*2.07*	57
	NPK holes	13.0	0.40	0.45	0.74	0.40	*1.59*	20
	None	13.0	0.35	0.36	0.61	0.36	*1.32*	...
Black walnut	N surface	10.3	0.71	0.53	0.74	0.55	*1.98*	254
	NPK surface	10.4	0.52	0.40	0.55	0.20	*1.47*	163
	NPK holes	10.9	0.51	0.50	0.64	0.49	*1.65*	195
	None	10.8	0.17	0.15	0.24	0.13	*0.56*	...

[a] 1965, 1966, and 1967 data only.

annual diameter growth after fertilization of each of the deciduous species was approximately 0.6 cm.

The large, closely spaced pines at Sinnissippi Forest did not increase markedly in trunk diameter following fertilization. The fertilized pines in one plot grew more than the untreated trees, while the fertilized pines in two plots grew less than the untreated trees.

Even on the sandy soil at this site, nitrogen was the single nutrient that produced a significant growth response. Ash and sycamore trees receiving NPK grew more than those receiving N alone. Walnut trees receiving NPK grew less than those receiving N alone. Increased growth due to fertilizers containing nitrogen was 204 percent for walnut, 76 percent for ash, and 29 percent for sycamore.

There was little difference in growth

response between surface and soil hole methods of application. There was a tendency for fertilizers applied in holes to give slightly less response than surface-applied fertilizers during the first year of treatment and to give slightly more response as a residual action in the year following application.

Lincoln Trail State Park

Fertilized trees in every plot at Lincoln Trail State Park grew more than the untreated trees. Loblolly pines and tulip trees grew moderately well without fertilizers during the period of this test but the persimmon, sweet gum, and sycamore trees grew slowly. The amounts of growth of treated and untreated trees are given in Table 21.

The four deciduous species responded with greater percentage increases in growth than did the loblolly pines. The treated persimmons and sycamores grew about three times as fast as untreated trees. The increased growth of treated over untreated trees was about 60 percent for tulip trees, about 40 percent for sweet gums, and about 30 percent for loblolly pines.

The trees fertilized with NPK did not consistently grow more than the trees receiving only N. Among the sweet gums and tulip trees, one plot of trees receiving NPK grew more than, while another grew less than, trees receiving N alone. Persimmons receiving NPK grew more than those receiving only N. Sycamores receiving NPK grew less than those receiving N alone.

One method of application at Lincoln Trail State Park was not consistently better than another. The sweet gums and tulip trees receiving NPK on the surface grew more than comparable trees fertilized with NPK in holes, while the reverse was true with sycamores. There was a tendency for the trees treated with NPK on the surface to respond more than trees treated either with NPK in soil holes or N on the surface.

Crab Orchard Wildlife Refuge

The three species of trees at Crab Orchard Wildlife Refuge—sweet gum, pecan, and black walnut—all responded favorably to fertilization. The amounts of growth of the treated and untreated trees are given in Table 22. Particularly

Table 21.—Trunk diameter growth of trees in the method-of-treatment fertilizer plots at Lincoln Trail State Park. Trees were fertilized in 1966, 1967, and 1968.

Species	*Treatment*	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm* 1966	1967	1968	*Total*	*Percent Increase Over Untreated*
Loblolly pine	N surface	14.4	0.64	1.42	0.65	*2.71*	32
	NPK surface	14.3	0.68	1.53	0.56	*2.77*	34
	None	12.4	0.54	1.07	0.45	*2.06*	. . .
Persimmon	N surface	9.3	0.35	0.50	0.56	*1.41*	143
	NPK surface	9.2	0.44	0.63	0.72	*1.79*	209
	None	9.3	0.22	0.19	0.17	*0.58*	. . .
Sweet gum	N surface	11.7	0.44	0.78	0.85	*2.07*	41
	NPK surface	10.8	0.42	0.85	1.03	*2.30*	56
	NPK holes	10.8	0.42	0.60	0.73	*1.75*	19
	None	10.2	0.37	0.51	0.59	*1.47*	. . .
Sycamore	N surface	8.1	0.80	1.37	0.96	*3.13*	273
	NPK surface	7.6	0.54	0.96	0.83	*2.33*	177
	NPK holes	7.6	0.62	1.04	1.01	*2.67*	218
	None	9.5	0.32	0.33	0.19	*0.84*	. . .
Tulip tree	N surface	10.6	0.70	1.03	1.48	*3.21*	48
	NPK surface	10.1	0.75	1.23	1.92	*3.90*	80
	NPK holes	10.5	0.72	1.00	1.44	*3.16*	46
	None	11.4	0.60	0.68	0.89	*2.17*	. . .

Table 22. — Trunk diameter growth of trees in the species response fertilizer plots at Crab Orchard National Wildlife Refuge. Trees were fertilized in 1966, 1967, and 1968.

Species	*Treatment*	*Average Initial Diameter, cm*	*Trunk Diameter Growth, cm* 1966	1967	1968	*Total*	*Percent Increase Over Untreated*
Sweet gum	N surface	9.5	0.20	0.36	0.39	*0.95*	16
	NPK surface	10.3	0.28	0.46	0.48	*1.22*	49
	NPK holes[a]	8.6	0.18	0.41	0.44	*1.03*	26
	None	10.2	0.23	0.26	0.33	*0.82*	...
Pecan	N surface	40.1	0.89	0.85	1.06	*2.80*	16
	NPK surface	39.1	0.89	0.92	1.03	*2.84*	19
	None	42.5	0.81	0.68	0.93	*2.42*	...
Walnut[b]	N surface	19.1		0.76	0.36	*1.12*	53
	NPK surface	15.2		0.69	0.33	*1.02*	40
	None	17.7		0.48	0.25	*0.73*	...

[a] N on surface in 1967 and 1968.
[b] Trees were fertilized in 1967 and 1968 only.

satisfying was the demonstrated diameter growth increase of at least 16 percent by the large, widely spaced pecan trees. Sweet gums increased their growth by more than 30 percent, and the walnuts increased theirs by more than 40 percent, following fertilization. Nitrogen was the nutrient that produced the significant growth response in all species; however, two plots of sweet gum receiving NPK grew somewhat more than one plot receiving N alone.

DISCUSSION AND CONCLUSIONS

Although there is certainly a need for more field trials to evaluate the effects of fertilizers on established deciduous trees, the requirements for carefully controlled experiments of this nature are exceedingly demanding. Uniformity of site, soil, and specimen material is essential. The ideal plant material should be from clonal stock. If seedling stock must be used, it should come from the same source and be collected, planted, and transplanted as a unit. It often requires 3 years for a seedling 1–1.5 m tall to become well established following transplanting. Growth during these years is limited.

A restricted soil area frequently limits tree growth because of competition among plants for available water, nutrients, or light. Visual observations of tree crowns are usually adequate for determining competition for light. Root distribution, however, varies with plant species and soil type and cannot be accurately estimated. Thus trees must be widely spaced, and not in competition with other trees, if meaningful measurements of increased growth due to the addition of nutrients are to be made. An experimental area containing established, uniform trees that are widely spaced on a uniform soil is rare.

Several factors have previously been used to measure the responses of trees to fertilizers, one of which is leaf color. The leaves on many trees become more green or darker green following the application of nutrients. Color data presented in an earlier report (Himelick, Neely, & Crowley 1965) were collected in 1963 and 1964 from plots at the Morton Arboretum. These data correlated well with the data from trunk diameter growth measurements.

Tree height, shoot growth, and trunk diameter growth can all be used to measure growth responses to fertilization. Each has advantages and disadvantages. Trunk growth extends throughout the growing season and the amount of this growth is influenced by the amount of soil moisture available. Trees must have an established root system before trunk diameter measurements will indicate growth stimulation due to fertilization. Shoot growth of many trees occurs during a relatively short period early in the growing season with possible recurrent flushes of growth later in the season. In other trees, however, shoot growth may occur over a longer period of time. Shoot growth has not been as well correlated with climatic factors as has trunk growth. The obvious difficulty of accurately determining the height of large trees, and the large number of measurements required for adequately sampling shoots on large trees, prohibited the use of these means of measuring tree growth in this study.

The results of this study on the responses of established trees to fertilizers do not indicate the need for radical changes from current practices in fertilizing trees. However, the results do give a good means of comparing time, rate, and method of fertilizer applications, and the nutrients that may stimulate growth response.

In our tests at five sites in Illinois, significant growth response was obtained only from nitrogen. This is not surprising, because nitrogen is the element that most frequently stimulates the growth of other plants. Moreover, an optimum supply of nitrogen is often lacking in most soils of inorganic origin.

The soils at the five test sites represented sandy soils, fertile deep topsoils of prairie origin, fertile shallow topsoils of forest origin, and infertile shallow topsoils with heavy clay subsoils. Regardless of soil type, nitrogen stimulated growth in deciduous trees. Other nutrients, although they were available in relatively low quantities in some of the soils, failed to stimulate growth when added as fertilizers.

The four sources of nitrogen used in these tests were equally beneficial. Ammonium nitrate, ammonium sulfate, and urea release nitrogen rapidly in the soil, making it readily available for plant use. Ureaform releases nitrogen more slowly. It is less effective in the first year of application but has a greater residual influence than the other nitrogen sources tested.

Soil surface, soil hole, and solution injection were almost equally effective methods of applying nitrogen fertilizers. There is a great difference, however, in the economic aspects of application by these three methods. Solution injection is slow and expensive because it requires soluble fertilizers and a hydraulic system for injection. Placing dry fertilizer in soil holes is slow, difficult, and expensive because it requires extensive time and manpower to prepare the soil holes and distribute the fertilizer. Broadcasting on the surface is fast, easy, and relatively inexpensive. It requires only a lawn fertilizer spreader and a nitrogen fertilizer.

In this study the growth response to foliar fertilization was extremely slight. The color response given in the preliminary report (Himelick, Neely, & Crowley 1965) was just as slight. Soil applications of fertilizers gave significant growth and color responses, while foliar applications did not.

The rate of application of nutrients used in these tests was an empirical figure. It was based on area of soil, not size of trees. Nitrogen at the rate of 29.3 g per sq m (6 lb per 1,000 sq ft) of soil area is commonly used for fertilizing established shade trees. Arborists placing dry fertilizers in holes use this rate commercially, and have found it nontoxic to trees and grass. Our results confirm the usefulness of the rate. The trees fertilized with one-half this rate grew less than half as much as the trees fertilized at this rate. The trees fertilized with additional nitrogen grew more, but the additional growth was insufficient to justify changing the recommendations. Higher rates of nitrogen applied to the surface during summer months were toxic to grass (Himelick, Neely, & Crowley 1965).

Spring applications of nitrogen were

more effective than summer and fall applications. The distinct advantage of April over October applications obtained in this study is not in agreement with the research of Jacobs (1929) or Chadwick (1941).

There is little in the results of this study on which to base recommendations on frequency of fertilization. In most of our tests, the trees were fertilized for 3 consecutive years. The amount of additional growth due to fertilization was relatively uniform each year with little or no cumulative effect. Within 2 years after fertilization ceased, the treated trees were growing at the same rate as the untreated trees.

Although 20 species of deciduous trees were included in this study, it is difficult to reach conclusions concerning the inherent capabilities or genetic limitations of tree species in response to fertilization. At four of the five sites the slow-growing tree species gave the greatest percentage increases in growth when fertilized, but they did not necessarily produce a greater volume of wood than the faster-growing trees. The slow-growing trees were the smaller trees at these sites. Tree size and tree competition rather than tree species more likely influenced the degree of response to fertilization.

At no time during the 6 years of this study was there injury to grass or understory plant material following surface application of N or NPK fertilizers. The fertilized understory plants became darker green and grew larger than comparable unfertilized plants. Fertilized trees grew more than unfertilized trees even with the additional competition from weeds and bluegrass turf.

In Illinois there usually is an adequate supply of rainfall during the months of April, May, and June. During the period of these tests, rainfall in April, May, and June usually amounted to 25–35 cm (10–14 inches) at each of the five tree fertilization test sites (Table 2). Periods of drought are more common during the other 9 months of the year. During one 3-month period rainfall totals may be two or three times greater in one year than in the same period of the previous year.

Annual variations in tree growth are partly determined by the amount of soil moisture present. Due to variability in frequency and intensity of rainfall and variability in soil characteristics, it is very difficult to determine soil moisture content from rainfall data. In an attempt to associate amounts of rainfall with tree growth, two correlations were found. There was little divergence of pin oak, white ash, and honey locust trees in the *method* test at Morton Arboretum from the pattern of little growth in 1963, increased growth in 1964, increased growth in 1965, decreased growth in 1966, increased growth in 1967, and decreased growth in 1968. Both the amount of rainfall from October through March, prior to the growing season, and the amount from June through August, during the growing season, were correlated with the trunk diameter growth of trees (Fig. 8). These correlations were found to exist on many species of trees at all five sites in this study.

Recommendations for shade tree fertilization to arborists and homeowners were prepared by Neely & Himelick (1966). The recommendations were based primarily on this study with additional information gleaned wherever possible from experiments in aboriculture, pomology, forestry, and agronomy.

SUMMARY

The responses of established trees to applications of fertilizers at five sites in Illinois were determined by annual trunk circumference measurements. As many as 16 treatments (each of the treatments a different combination of fertilizer and method or time or rate of application) were used on 20 species of deciduous trees and 2 species of evergreens. Four methods of application were used: surface broadcasting, placement of dry

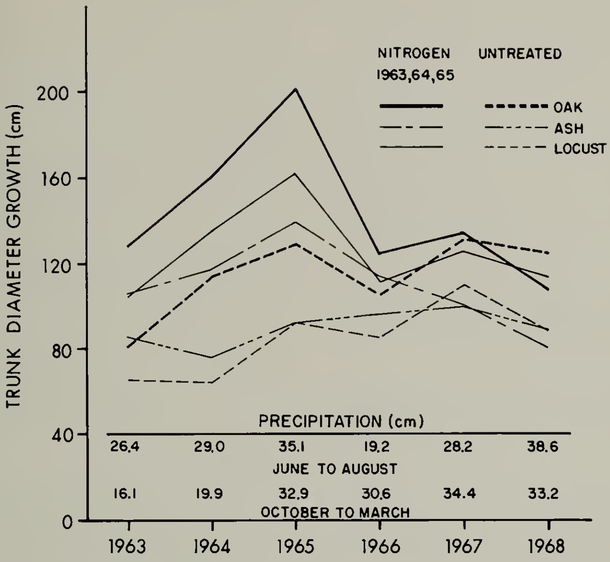

Fig. 8.—The diameter growth of three species of trees in the method test at Lisle was correlated with the quantity of precipitation occurring in (i) 6 fall and winter months prior to the growing season and (ii) 3 summer months during the growing season.

fertilizers in holes in the soil, injection of liquid fertilizers into the soil, and spraying of foliage. The following nutrient elements or combinations of elements were used: N, PK, NPK, and NPK plus minor elements.

When elemental nitrogen was added to the soil at the rate of 29.3 g per sq m (6 lb per 1,000 sq ft), tree growth increased significantly. Increased growth persisted only 1 or 2 years after treatment ceased. April applications increased growth more than October applications.

The application of phosphorus and potassium to the soil did not bring about a significant growth response; nor did a combination of phosphorus, potassium, and nitrogen produce a response that was significantly greater than that produced by nitrogen alone. The addition of minor elements to NPK produced no significant growth response.

The three methods of soil application appeared to be about equally effective, with minor variations among the tree species. Foliar sprays did not produce a substantially greater growth than the growth of unfertilized trees.

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